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Revealing complex aspects of compressive failure of polymer composites – Part II: Failure interactions in multidirectional laminates and validation

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The compressive failure of multidirectional laminates can be considered as an interaction of four failure mechanisms: fiber kinking, fiber splitting, matrix cracking and delamination. The interaction of these four failure mechanisms is responsible for the macroscopically observed nonlinear behavior and ultimate failure of the structure.

In this paper, a numerically efficient 3D Finite Element modeling approach is presented combining the benefits of homogenizing material models and micromechanical modeling strategies. The micro model is used to resolve the regions which are prone to fiber kinking. In all other regions, a single UD ply is considered as a continuum (i.e. in a homogenized way) and the material properties are represented using a transversely-isotropic constitutive model. At both scales, fully 3D elastic–plastic material models regarding nonlinearities and failure under multiaxial loading conditions are used.

With this approach, the progressive failure of multidirectional laminates under compressive loading can be simulated in detail considering the complete kinking process and the progression of kink bands. The sequence and interaction of the different failure mechanisms is studied and discussed. In order to validate the numerical results, the nonlinear stress–strain response and ultimate failure stress of selected carbon epoxy laminate layups is predicted and compared with experimental results.

1. Introduction

Fiber kinking is typically limiting the compressive strength of fiber reinforced composites. In earlier studies of fiber kinking, an elastic buckling of aligned fibers was assumed by Rosen [24]. It is now widely acknowledged that initial fiber misalignments accompanied by matrix nonlinearities are responsible for the initiation of kink bands. This observation was published first by Argon [3]. It was found by experiments and numerical models that the initiation and propagation of kink bands is an evolutionary process which starts with local matrix yielding at fiber misaligned areas and continues to form a yield band which enables the fiber bending and the creation of a kink band, see Ravi-Chandar et al. [22], Kyriakides and Ruff [14] and Bishara et al. [4].

The interaction between fiber kinking and other failure mechanisms was observed in various testing results of unidirectional laminates, multidirectional laminates and woven composites under compressive loading. Soutis [25] examined the compressive failure of multidirectional laminates using T800/924C carbon-epoxy, His results demonstrated that with a fractographic study it is very difficult to evaluate the ply-interactions because of the extensive post-failure damage. Soutis and Turkmen (1997) continued working on the prediction of compressive strength. They tested a single unidirectional laminate of T800/924C carbon-epoxy, where catastrophic failure caused by the fiber kinking mechanism was observed. They concluded that longitudinal splits and fiber/matrix debondings occured suddenly and concurrently with the final failure. In Lee and Soutis [15,16], the compressive strength of thick carbon fiber-epoxy laminates is studied for two carbon-epoxy systems: T800/924C and IM7/8552. According to Lee and Soutis [15,16], the failure of multidirectional laminates involves a combination of four mechanisms: (a) fiber kinking in 0° plies; (b) delamination between 0° and $\pm 45^\circ$ plies; (c) splitting parallel to the fiber at 0° and $\pm 45^\circ$ plies; (d) matrix cracking in the 90° plies. The crushing failure mode occurred without global buckling. Pinho et al. [19] tested T300/913 laminates with $[0, 90_2, 0]_{3S}$ layup. Out-of-plane kink bands, matrix cracking in the 90° plies

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and delamination close to the kink bands were observed under compression. Similar observations are presented in the work of Soutis in Talreja and Varna [26]. The coupling between modeling approaches was used in the simulation of compressive failure by kinking in laminated composites, see Allix et al. [2] and Prabhakar and Waas [20]. Allix et al. [2] applied a hybrid description of the material by using elementary cells to predict the fiber kinking and interfaces to represent splitting and delamination. Prabhakar and Was [20] developed an up-scaling approach from the micro-model to capture laminate failure due to fiber kinking. An 8-plies model was up-scaled using this approach by homogenizing the off-axis plies and retaining micro-mechanics in the 0° plies. The predicted compressive strength was limited by kink-banding instability and delamination was not accounted for.

The experimental results are able to show the failure mechanisms which occur inside the composite, but the sequence of failure events and their interaction is still not fully understood. However, a deeper understanding of these interactions is important in order to develop capable analytical models and, finally, in order to improve the mechanical properties of composite materials under compression. With the hybrid micro meso model presented hereafter, the complete compressive failure of multidirectional laminates including fiber kinking is studied. The initiation and propagation of kink bands are properly represented, so that the interactions during the kinking process can be studied. Material nonlinearities are regarded both at micro- and meso-scale. With this modeling approach, the complete nonlinear response of multidirectional laminates can be predicted and the interaction of different failure mechanisms can be investigated. In order to validate the hybrid micro meso modeling approach, the obtained numerical results are compared with experimental data from literature.

2. Hybrid micro meso modeling approach

Since experiments require high efforts in cost and time, finite element multiscale analysis represents a very useful alternative to real material tests. However, sophisticated material models which take into account the nonlinear material behavior under multiaxial loading conditions are required at different scales. The material behavior of a unidirectional ply of carbon-epoxy is driven by the material properties of the two constituents fiber and matrix and by the interaction of the two constituents. Under certain loading scenarios, like transverse compression and off-axis compression loadings, it is possible to homogenize such a UD ply using a transversely isotropic constitutive model, see Ernst [6], Melro [17], Vogler et al. [28] and Camanho et al. [5]. In contrast to that, on-axis compression is still a big challenge due to the phenomenon of fiber kinking. The complexity of this failure mechanism prevents the description of progressive damage in a homogenized way at ply level. In the regions prone to kinking a micro modeling approach should be used, i.e. matrix and fibers should be modeled separately in order to account for the interactions of fiber and matrix and of the different failure mechanisms leading to the formation and propagation of a kink band. Two difficulties arise in this context: firstly, the pronounced nonlinearities in the progressive failure response and, secondly, the complex propagation of the kink band through the ply where matrix yielding and fiber breakage occur.

Based on the previous observations, the objective of this paper is to combine the benefits of homogenizing constitutive models used at ply level (we call it meso-scale here) and of the micro modeling of fiber and matrix in regions where kink bands are supposed to occur. Accordingly, the hybrid micro meso model is based on a micromechanical model discretizing fibers and matrix in the kinking-relevant areas (i.e. axial loadings or loadings in fiber directions) and on a meso modeling approach at ply level in all other areas where fiber kinking is not expected to occur.

On the micro-scale an isotropic elastic–plastic constitutive law is used for the matrix and an orthotropic elasticity model with linear damage is used for the fibers. In the region that is resolved by the micro model, matrix yielding, initiation and development of kink bands, fiber bending and breakage can be investigated. Elsewhere, fiber kinking is disregarded and the meso model is used. The UD plies are represented in a homogenized way using a transversely isotropic elastic–plastic constitutive model for each ply. With this modeling approach, the nonlinear behavior and the cracks in the 90° and 45° plies can be predicted. It should be noted that the numerical cost of the micro model is much higher compared to the transversely isotropic model used at meso-scale that the meso model is far more efficient. Consequently, the micro model should be used just in the regions where fiber kinking is supposed to occur.

In this work, the initiation and propagation of kink bands are properly represented, so that the interaction during the kinking process can be simulated and the complete nonlinear stress–strain response can be determined. Fig. 1 shows a five plies laminate with the layup [90°, 0°, 90°, 0°, 90°]. Under pure compression loading, fiber kinking is supposed to occur in the 0° ply. Consequently, only the micro model is used for the 0° ply, whereas the 90° plies are considered in a homogenized way using the transversely isotropic model. The homogenized constitutive model is able to predict the nonlinearity and cracks in the 90° and 45° plies. Due to the fact that delamination occurs in the interfaces between the plies, two scenarios are expected: delamination between meso-meso modeled plies and delamination between micro-meso modeled plies. In both cases, the material laws (i.e. isotropic for the matrix and transversely isotropic for the meso-scale) are able to predict the fully nonlinear behavior and the damage behavior due to the expected stress concentrations in these interfaces.

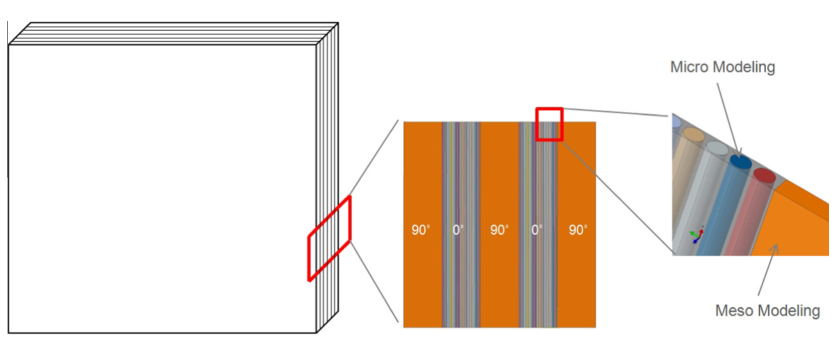

Fig. 1. Hybrid micro meso modeling approach for MD-Laminates under compression.

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